CDF note 8004

# $B_c^- \to J/\psi\ \pi^-$ at CDF with 1.1 fb$^{-1}$


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A search is made for the exclusive decay $B_c^- \to J/\psi\ \pi^-$ in $\sim$1.1 fb$^{-1}$ of CDF Run II data. This analysis emphasizes the removal of background by tuning selection requirements on the $B^- \to J/\psi\ K^-$ signal and sideband background regions using the data. We fix the selection requirements before looking at the M($J/\psi\pi$) distribution for $B_c^-$.

We observe 79 events with an invariant mass between 6245 and 6305 MeV/$c^2$ of which 44.4 are attributed to $B_c^-$ signal and 34.6 are attributed to background. We determine the significance of this observation to be greater than $6\sigma$. We measure the mass of the $B_c^-$ meson:

$$\text{Mass}(B_c^-) = 6276.5 \pm 4.0 \pm 2.7\ \text{MeV}/c^2$$

## I. INTRODUCTION

We search for the $B_c^- \to J/\psi\ \pi^-$ decay [1] with $\mathrm{J}/\psi \to \mu^+\ \mu^-$ and a charged pion in order to obtain a sample of fully reconstructed $B_c^-$ decays. The goal of the analysis is to perform an unbiased search with respect to the final $\mathrm{M}(J/\psi\ \pi^-)$ mass distribution in order to establish a statistically valid significance and mass measurement.

Because large theoretical uncertainties in the $B_c^-$ production and decay properties resulted in more than a factor of ten uncertainty in the *a priori* $B_c^-$ signal expectation estimates, we have chosen an analysis strategy that is relatively uncomplicated (*i.e.* a cut-based analysis) with selection requirements first driven by resolution effects. The key to this analysis is the removal of large combinatorial backgrounds by well-motivated and S/N-enhancing selection requirements especially on the third track to be added to the $J/\psi$. We derive these data-driven selection requirements using the reference $B^- \to J/\psi\ K^-$ decay.

The analysis is performed in an unbiased manner in that the selection was fixed before looking at the $J/\psi\ \pi^-$ mass distribution. After 0.36 fb$^{-1}$ and the analysis technique was approved, the "box was opened" and a small excess is observed around 6280 MeV/$c^2$. This excess was similar to that observed in a separate CDF analysis [2]. The excess was below our initial goals of being sufficient to claim at least a $5\sigma$ observation, so we have waited for additional data to be processed and validated. We now report the status of the analysis using approximately 1.1 fb$^{-1}$ and do observe a significant $B_c^-$ signal and we measure its mass with the current world's best precision.

## II. THEORY

The $B_c^-$ meson is a unique system composed of a heavy quark and a distinct heavy anti-quark which impacts its production, decay, and mass properties. The $B_c^-$ production properties in a $\overline{p}p$ colllider are not well-understood since non-perturbative QCD effects are important [3]. Hence, experimental measurements of production properties are expected to provide tests of theoretical calculations.

The decay properties of the $B_c^-$ are also influenced by the presence of both the $b$ and $c$ quarks. In particular, since either quark may participate in the decay, the $B_c^-$ lifetime is expected to be shorter than the $B^-$. While we have used distributions from the full $B^- \to J/\psi\ K^-$ sample to define our selection requirements, we have, in addition, focused on the subset of $B^-$ events with a $c\tau$ between 80 and 300 $\mu$m where the majority of significantly displaced $B_c^-$ events are expected. We have also studied some of our selection variables in greater detail as a function of $c\tau$ and $P_T$ in order to ensure that each variable is well-behaved and understood for relatively small displacements from the primary vertex. We note that CDF has measured the $B_c^-$ lifetime [4] using semi-leptonic decays that is consistent with the expectations:

$$\tau(B_c^-) = 0.463^{+0.073}_{-0.065}(\mathrm{stat}) \pm 0.036(\mathrm{syst})\ \mathrm{ps}$$

The mass of the $B_c^-$ is not well-known theoretically and has been estimated using potential models and QCD sum rules [5] [6]. The predicted mass range found in these calculations span from approximately 6150 to 6500 MeV/$c^2$. Lattice QCD has also been employed to calculate the $B_c^-$ mass (more precisely, a mass difference such as between an $\Upsilon$ meson and the $B_c^-$) using the quenched approximation [7] and relatively recent unquenched methods [8]. The results of the recent unquenched calculations have the smallest theoretical uncertainties:

$$\mathrm{M}(B_c^-) = 6304\ \pm\ 12\ ^{+18}_{-0}\ \mathrm{MeV}/c^2(\mathrm{Lattice\ theory})$$

It is interesting to compare our final result with the recent lattice calculation. It is hoped that such comparison results in further improvements in theoretical calculations.

## III. SELECTION REQUIREMENTS

The selection requirements are chosen to give a large $B^- \to J/\psi\ K^-$ signal with very small background to improve the possibility of a significant $B_c^-$ observation. We consider the kinematic transverse momentum requirements on the third track and the $B$ candidate where we expect harder distributions from the signal. We require the lifetime ($c\tau$) be positively displaced and have its uncertainty determined with good precision. We require the $\chi^2$ of the combined vertex and $J/\psi$ mass constrained fit algorithm have a fit probability above a certain value. We require the displaced $B$ candidate point to the primary vertex both in terms of a pointing angle, $\beta$, and in terms of having a small impact parameter significance. For the third track, we require the impact parameter with respect to a secondary vertex determined by the $\mathrm{J}/\psi \to \mu^+\ \mu^-$ candidate to be small and the impact parameter significance with respect to the primary vertex to be large.

We consider the reference decay $B^- \to J/\psi\ K^-$. After selecting $J/\psi \to \mu^+\ \mu^-$ candidates using muon quality requirements and requiring the dimuon mass to be within 70 MeV/$c^2$ of the world average $J/\psi$ mass, we apply the "standard selection" shown in Tab. I. In our studies, we have noticed a substantial $B^- \to J/\psi\ K^-$ signal in the events that fail exactly one of the standard selection requirements. For the subset of these events at higher $P_T$ with $P_T(K) > 2.5$ GeV/$c$ and $P_T(J/\psi\ K) > 6$ GeV/$c$, we require the additional *tighter* "High-$P_T$ selection" except that an event may fail one of the tighter requirements. Fig. 1 shows the reconstructed $B^- \to J/\psi\ K^-$ signal for the events that pass the standard selection alone and the events that are selected from either the standard selection or high-$P_T$ selection. The *recovered* high-$P_T$ selection results in an increase of the $B^-$ yield by 27%. The total signal of 11300 $B^-$ candidates with a small background of 250 events in the region between 5.4 and 5.5 GeV/$c^2$ suggests that this selection will be relevant for seeking out a $B_c^- \to J/\psi\ \pi^-$ signal at higher mass where the only change is the assignment of a pion versus kaon mass hypothesis to the third track that is combined with the $J/\psi$.

| Selection variable | Standard | High-$P_T$ |
|---|---|---|
| $P_T(K)$ | $> 1.7$ GeV/$c$ | $> 2.5$ GeV/$c$ |
| $P_T(J/\psi\ K)$ | $> 5$ GeV/$c$ | $> 6$ GeV/$c$ |
| $c\tau(J/\psi\ K)$ | $> 80\ \mu$m | $> 100\ \mu$m |
| $\delta[c\tau(J/\psi\ K)]$ | $< 30\ \mu$m | $< 25\ \mu$m |
| $Prob(\chi^2_{\mathrm{Con.fit}})$ | $> 0.1\%$ | $> 1\%$ |
| Pointing angle, $\beta$ | $< 0.4$ radians | $< 0.3$ radians |
| $\lvert ip_{\mathrm{signif}}(J/\psi\ K\mathrm{wrt\ p.v.})\rvert$ | $< 2.5\sigma$ | $< 2\sigma$ |
| $ip(K$ wrt s.v.) | $< 100\mu$m | $< 80\mu$m |
| $\lvert ip_{\mathrm{signif}}(K\mathrm{wrt\ p.v.})\rvert$ | $> 2.5\sigma$ | $> 3\sigma$ |

TABLE I: Selection variables and requirements for the standard selection and high-$P_T$ selection as described in the text. Here "$K$" refers to the third track combined with the $J/\psi$ and may be a kaon or pion candidate for the $B^-$ or $B_c^-$ respectively..

## IV. $B_C^- \to J/\psi\ \pi^-$ RECONSTRUCTION

Figure 2 shows the candidate $B^- \to J/\psi\ \pi^-$ events under the combined standard and high-$P_T$ selection. The data is shown with identical binning with different mass regions highlighted. A clear excess is evident around 6280 MeV/$c^2$. Figure 3 shows the excess growing as a function of including additional integrated luminosity.

## V. SIGNIFICANCE OF THE $B_C^-$ SIGNAL

We first acknowledge that a statement of significance of an excess of events has a subjective component. Nevertheless, we calculate several numbers that are well-defined and indicative of the significance of our observed excess.

### A. Binned fit and Poisson probability

We perform a binned fit using a linear background and Gaussian signal shape for the $B_c^-$ data. Figure 4 shows the result of the fit where an excess is found at $6276.6 \pm 3.6$ MeV/$c^2$. The fit was performed by fixing the width of the Gaussian to $\sigma_R = 15.5$ MeV/$c^2$ where $\sigma_R$ is the expected mass resolution using the observed $B^- \to J/\psi\ K^-$ width in the data and scaling by a factor suggested by a Monte Carlo simulation. In the region that is approximately $\pm\ 2\sigma_R$ wide between 6245 MeV/$c^2$ and 6305 MeV/$c^2$ the total number of events in the data is 79. Subtracting the fitted background distribution as seen in Fig.5 suggests 44.4 $B_c^-$ signal events on a background of 34.6 within this mass window. The Poisson probability that 34.6 background events can flutuate to a total number of events exceeding 79 is $3.0 \times 10^{-11}$ which would correspond to $6.5\sigma$. If one estimates 10 independent bins in a wider search window of 300 MeV/$c^2$ with the probability reduced by a factor of 10, the corresponding Gaussian sigma would then be $6.2\sigma$.

### B. Toy Monte Carlo studies

We have performed a Toy Monte Carlo study with trials that mimic our understanding of the background to determine the probability that the background might fluctuate into an excess like we observe. We consider a 300 MeV/$c^2$ wide search window between 6150 and 6450 MeV/$c^2$ for the $B_c^-$ as suggested by the range of theoretical predictions.

The Toy Monte Carlo study was performed with high statistics using the fitted background from data. For each trial, the largest number of events in a 60 MeV/$c^2$ range is tabulated. This random fluctuation is treated as a "signal" and the effective signal above background at the mass of the "signal" is calculated. Fig. 6 shows the distribution of $S/\sqrt{B}$ for $10^8$ trials. We find our observation at $S/\sqrt{B} = 7.5$ to be above the tail of the generated distribution. An extrapolation suggests that a p-value of less than $10^{-11}$. This would correspond to 6.7 $\sigma$.

### C. Significance conclusion

We have evaluated several quantities that are indicative of the significance of the $B_c^-$ excess that we observe. These calculations show that the excess is above the $6\sigma$ level.

## VI. MASS OF THE $B_C^-$ MESON

The mass of the $B_c^-$ is determined precisely because the large tracking volume in CDF with small drift cells allows for excellent momentum resolution. The momentum resolution and vertex resolution is enhanced with silicon hit information including good coverage by the L00 detector mounted on the beam pipe. This tracking system has been extensively calibrated and used previously to measure the masses of $B$ mesons in Run II [9].

### A. Mass determination

In order to determine the mass of the $B_c^-$ meson, we perform an unbinned log likelihood fit to a linear background and a Gaussian signal where the signal fraction, the background slope, and a scale factor for each event's mass resolution are parameters of the fit in addition to the mass. In the fit for the $B_c^-$, we fix the scale factor for each event's mass resolution to 1.56 which is the scale factor found in the unbinned log likelihood fit for the $B^- \to J/\psi\ K^-$ decay. A similar scale factor of 1.48 is found for $B_s^0 \to J/\psi\ \phi$ decays and slightly larger factors of 1.89 and 2.11 are found for $B^0 \to J/\psi\ K_S^0$ and $\Lambda_B \to J/\psi\ \Lambda^0$ decays respectively, which have a longer-lived daughter particle.

The results of the unbinned fit show 49.1 $\pm$ 9.7 signal events above 34.1 background events (in a 60 MeV/$c^2$ region under the signal). The result of this fit gives a mass of 6276.5 $\pm$ 4.0 MeV/$c^2$ that agrees well with the binned likelihood fits shown in Fig. 4. We take this unbinned fit result as the central value of our measurement.

### B. Cross checks of the mass measurement

As a cross-check, we reconstruct other larger statistics B hadron decay modes and compare with the Run II measurements [9]. This comparison is presented in Tab. II. We see very good agreement.

| Decay | CDF pub | | Binned fit | | Unbinned fit | |
|---|---|---|---|---|---|---|
| | Mass | $\sigma$(M) | Mass | $\sigma$(M) | Mass | $\sigma$(M) |
| $B^- \to J/\psi\ K^-$ | 5279.1 | 0.5 | 5279 | 0.3 | 5278.7 | 0.2 |
| $B^0 \to J/\psi\ K_S^0$ | 5279.6 | 0.6 | 5280 | 0.5 | 5280.3 | 0.5 |
| $B_s^0 \to J/\psi\ \phi$ | 5366.0 | 0.6 | 5366 | 0.6 | 5366.1 | 0.5 |
| $\Lambda_B \to J/\psi\ \Lambda^0$ | 5619.7 | 1.7 | 5621 | 1.4 | 5620.6 | 1.4 |

TABLE II: B Hadron masses reconstructed with the same framework as the $B_c^-$ analysis compared with CDF results submitted for publication. For the CDF pub. results, the uncertainty is the combined statistical and systematic uncertainty. For the cross-checks of this work, only the statistical uncertainty is shown.

### C. Systematic uncertainties

For an evaluation of systematic uncertainties, we use studies that have been performed for the other $B$ meson masses [9]. For this to be valid, we first compare event-by-event mass differences between events in these studies as shown in Fig. 7. The agreement is very good with a mean difference of 0.6 $\pm$ 0.3 MeV/$c^2$. We compare the fitted $B^- \to J/\psi\ K^-$ mass in the eight run ranges as shown in Fig. 3 where each incremental run range is tabulated separately. In Figs. 8,9, we find the mean masses of the $B^-$ meson to be within 1.5 times the statistical uncertainty when comparing each subset to the entire sample. Thus, there are no major run dependent effects. We assign a systematic of 0.6 MeV/$c^2$ due to the observed difference in the event-by-event masses as a "calibration systematic."

Having established a mass scale, we consider other relevant systematic effects. The uncertainty in the momentum scale gives a 0.6 MeV/$c^2$ uncertainty as shown in Fig. 10 for the 3043 MeV/$c^2$ Q-value of the $B_c^- \to J/\psi\ \pi^-$ decay. We also assign 0.2 MeV/$c^2$ uncertainty each to an uncertainties that depend on track types and uncertainties due to the fact that the $\pi$ may have different radiative behavior compared with a $K$ [2]. These systematic effects combine to result in an uncertainty of 0.7 MeV/$c^2$ which is assigned as a "tracking systematic."

Our major systematic uncertainty comes in the small statistics fitting procedure. In particular, we find that the scale factor associated with the mass uncertainty prefers to find a value, if left to float, of 0.73±0.19 compared with 1.56 for $B^- \to J/\psi\ K^-$. The best fit to our $B_c^-$ signal appears to favor a very narrow Gaussian compared with the expected 15.5 MeV/$c^2$ resolution despite a very good C.L.=87.9% for the binned fit of Fig. 4 with the width fixed at 15.5 MeV/$c^2$. If the scale factor is allowed to float, we obtain a fitted mass at 6281.3 MeV/$c^2$ or 4.8 MeV/$c^2$ from our central value. To assign a systematic uncertainty, We study the resultant mass determination if we restrict the mass scale factor to be within reasonable values of 1.25 and 2.0. These values are set at about 20% below and above the scale factor from $B^- \to J/\psi\ K^-$ decays. We find the result of the unbinned log likelihood fits to be 6278.7 MeV/$c^2$ and 6273.8 MeV/$c^2$ respectively or a difference of 4.9 MeV/$c^2$. We assign a systematic equal to half of the difference of the 4.9 MeV/$c^2$ or a total of 2.5 MeV/$c^2$ as a systematic for our "fitting procedure."

The combined systematic uncertainty is the sum in quadrature of the uncertainties in our calibration, tracking, and fitting procedure. The total systematic is determined to be 2.7 MeV/$c^2$.

## VII. CONCLUSIONS

We have performed an analysis to search for fully reconstructed $B_c^-$ mesons using an unbiased selection based upon studies of the reference $B^- \to J/\psi\ K^-$ decay. When we apply the selection requirements and change the assignment from a kaon to a pion, we observe a data distribution shown in Fig. 11. We observe the $B_c^- \to J/\psi\ \pi^-$ signal at a significance larger than $6\sigma$ and have measured the mass of the $B_c^-$ meson to be 6276.5 ± 4.0 ± 2.7 MeV/$c^2$.

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[1] References to a particular charge state also imply the charge conjugate state unless explicitly noted.
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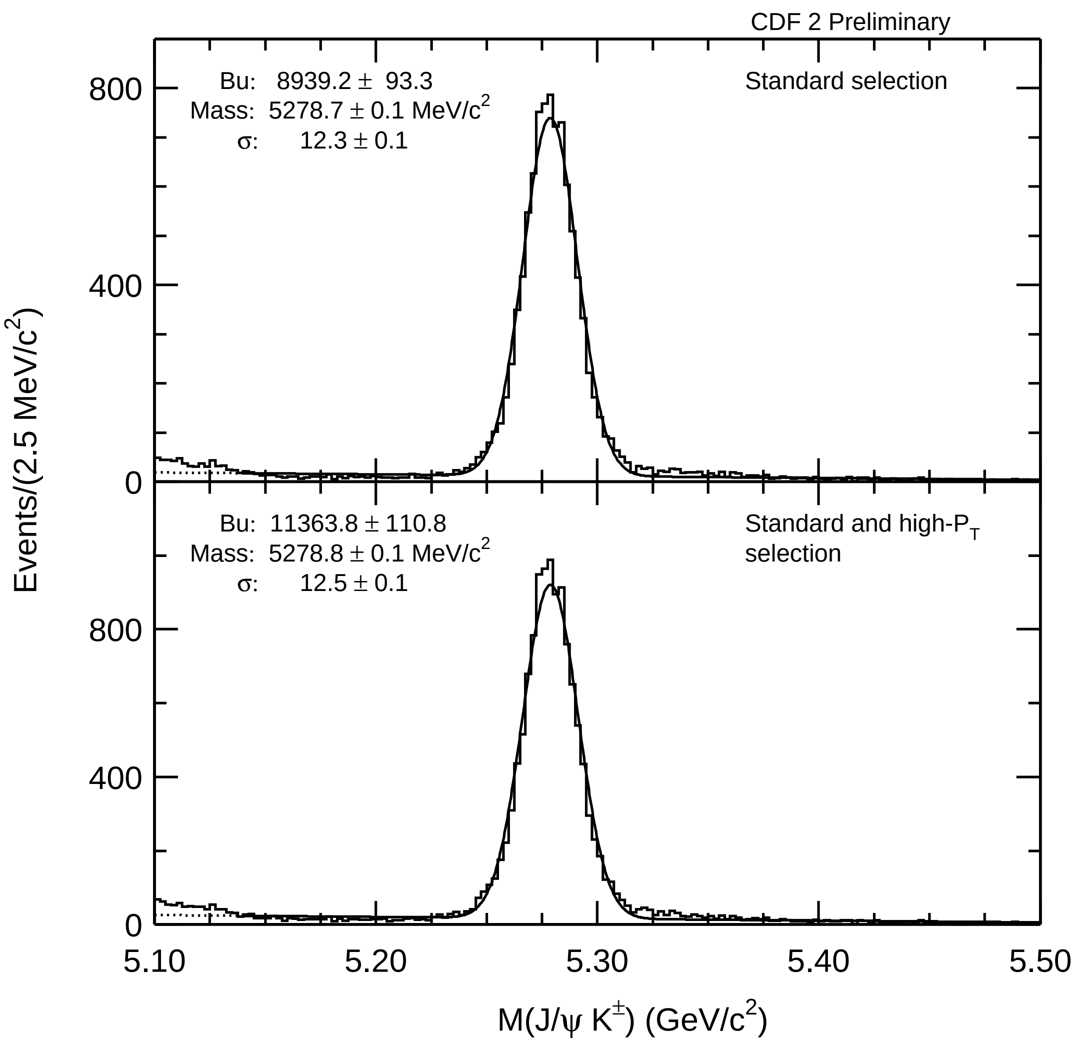


FIG. 1: $J/\psi\ K$ mass distribution with the standard selection (top) and with the standard and high-$P_T$ selection (bottom).

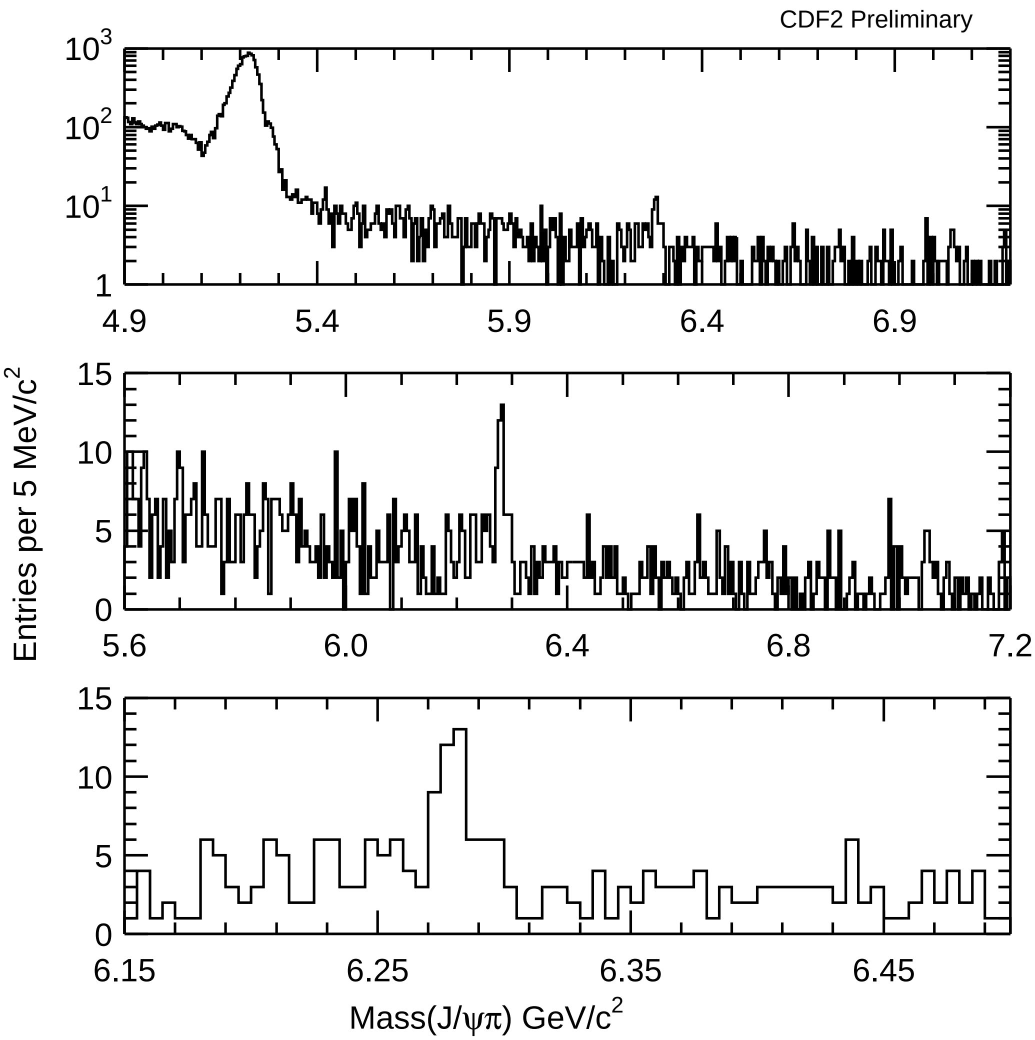


FIG. 2: $J/\psi\pi$ mass distribution in the a 4.9 to 7.2 GeV/$c^2$ mass range (top), 5.6 to 7.2 GeV/$c^2$ range (middle), and 6.15 to 6.5 GeV/$c^2$ range (bottom).

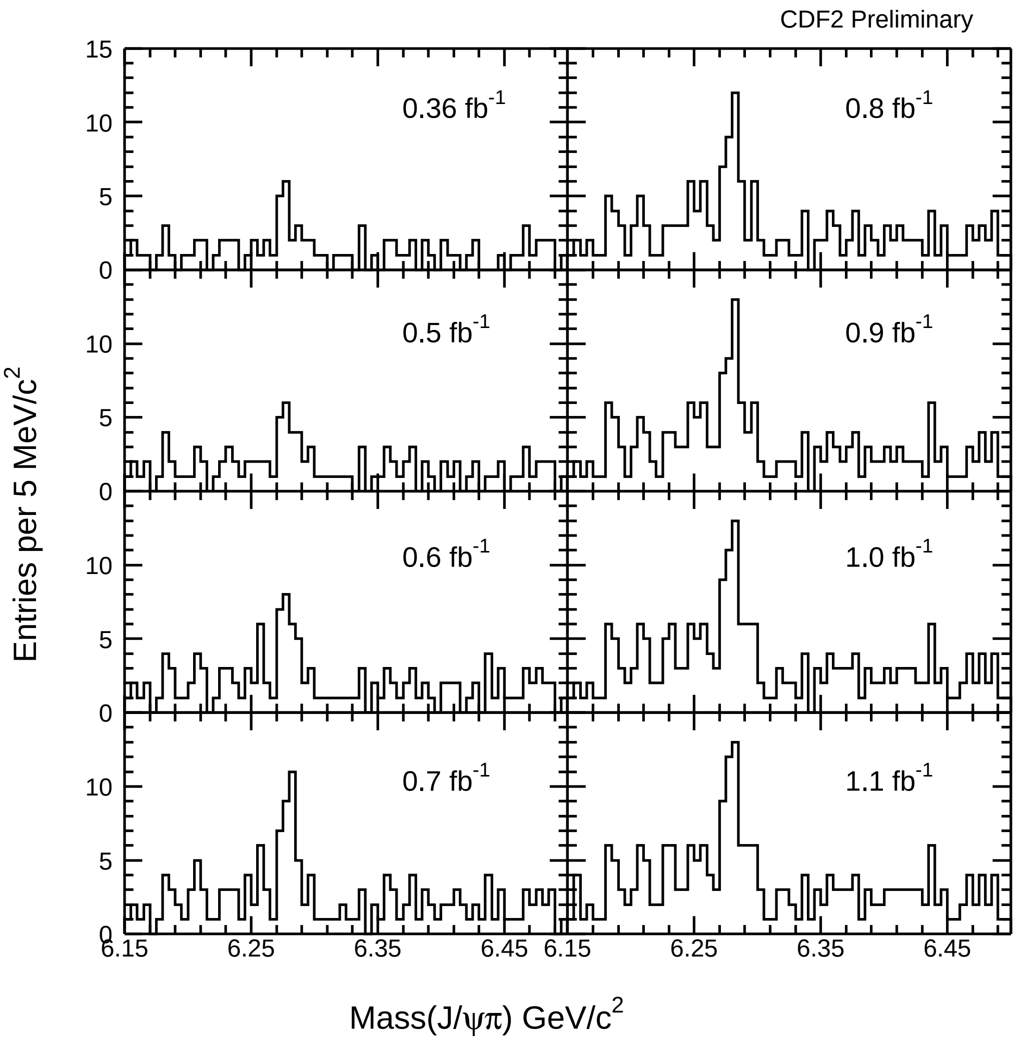


FIG. 3: $J/\psi\pi$ mass distribution for different integrated luminosities as data accummulated.

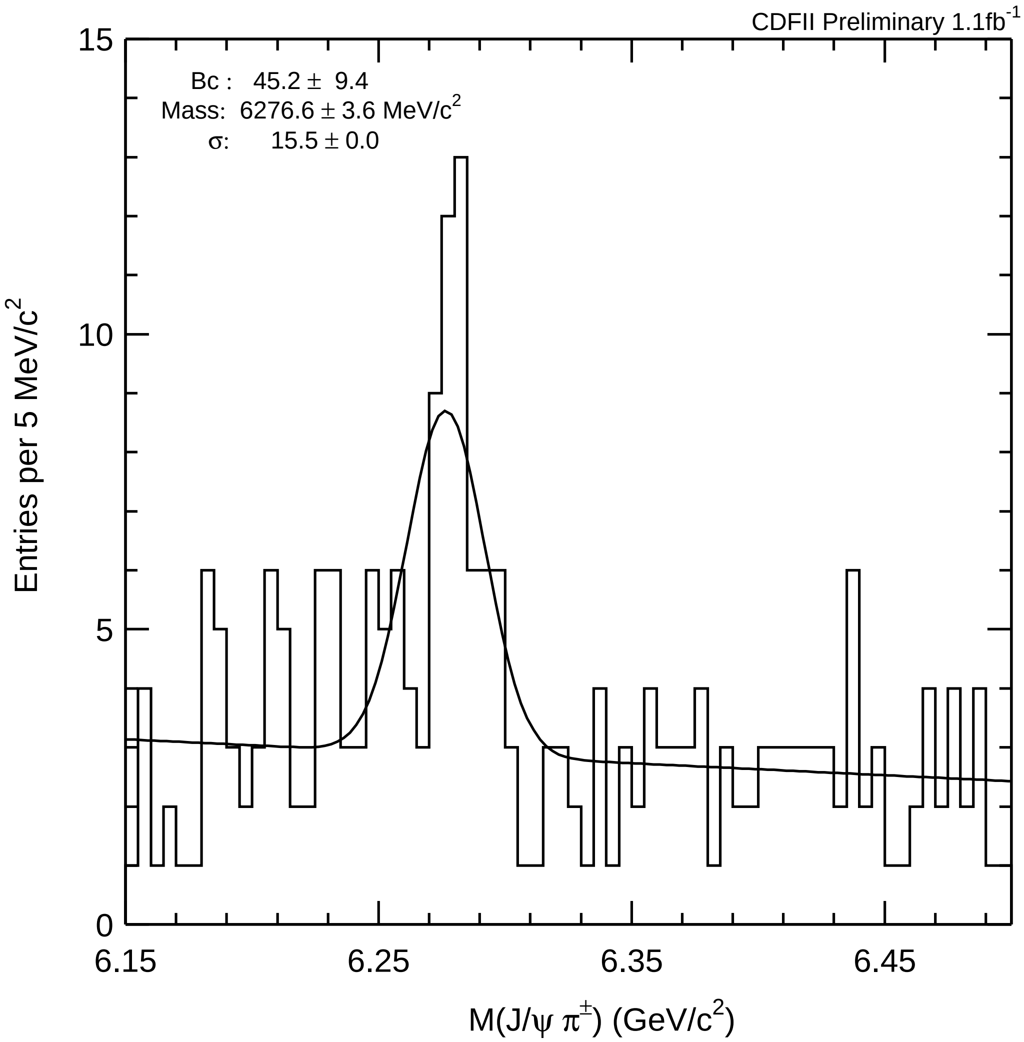


FIG. 4: $J/\psi\pi$ mass distribution in the 6.15 to 6.5 GeV$/c^2$ range with a superimposed Gaussian plus linear background binned fit.

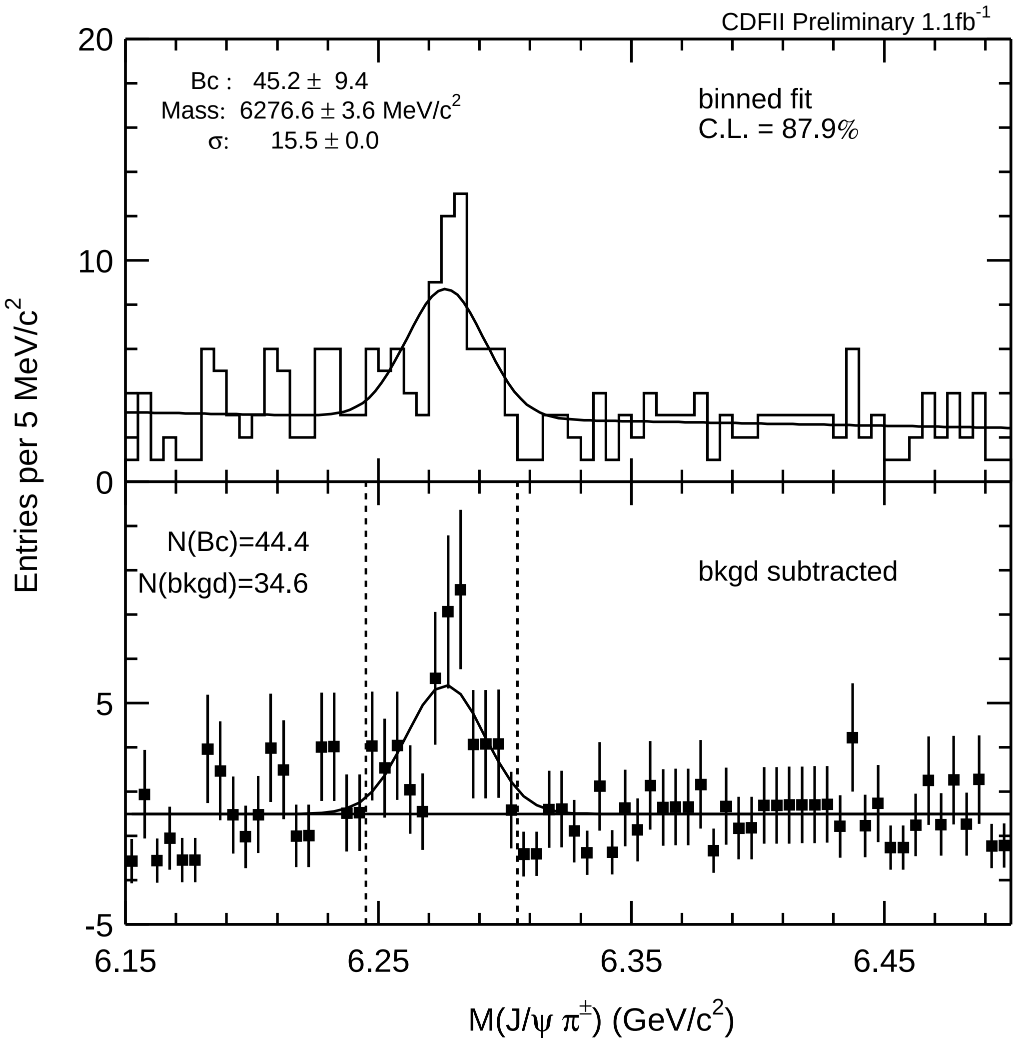


FIG. 5: $J/\psi\pi$ mass distribution in the 6.15 to 6.5 GeV/$c^2$ range with a superimposed Gaussian plus linear background binned fit (top). The $J/\psi\ \pi^-$ mass distribution with the linear background subtracted is shown (bottom) along with the number of events above background, N($B_c^-$) and the background in the 60 MeV/$c^2$ region between 6.245 and 6.305 GeV/$c^2$.

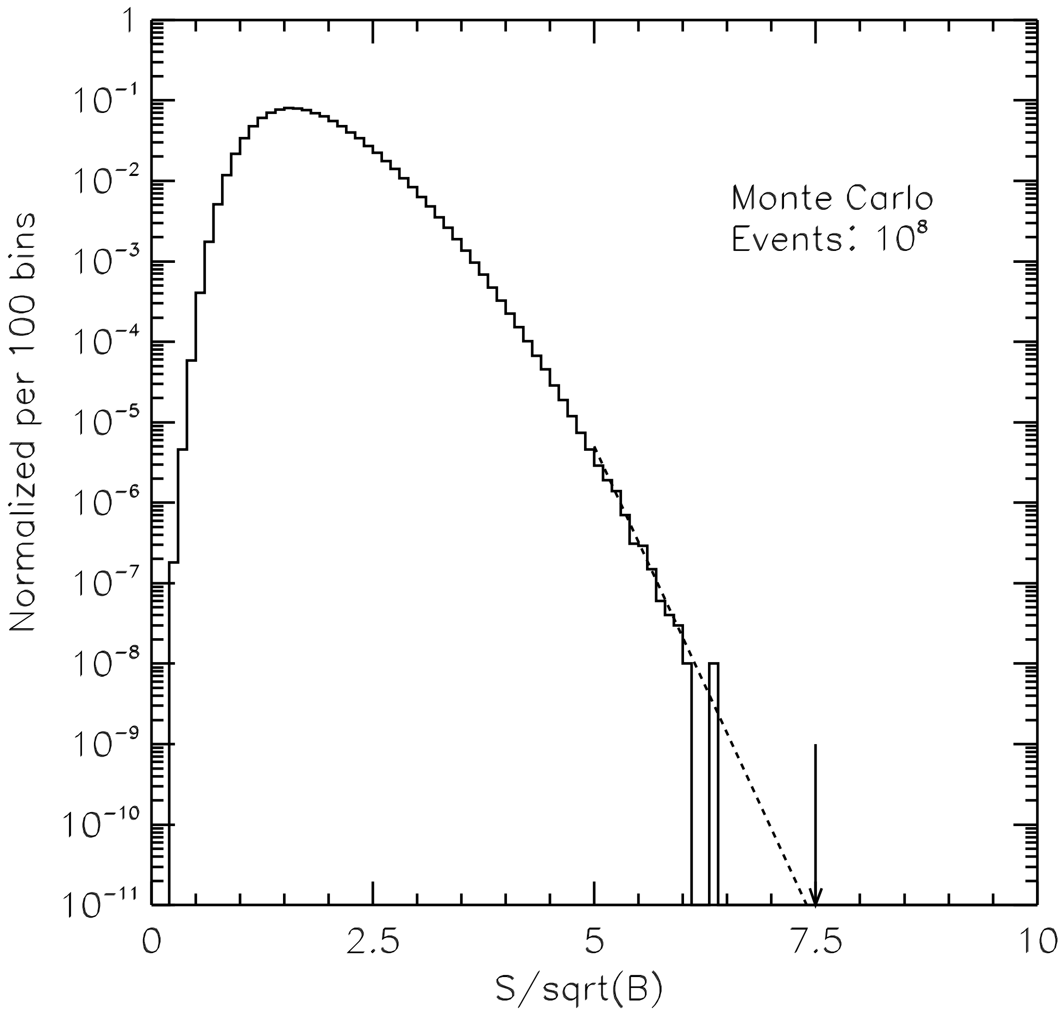


FIG. 6: Distribution from $10^8$ Toy Monte Carlo trials of the number of signal events above the square root of the background in a 60 MeV/$c^2$ wide window.

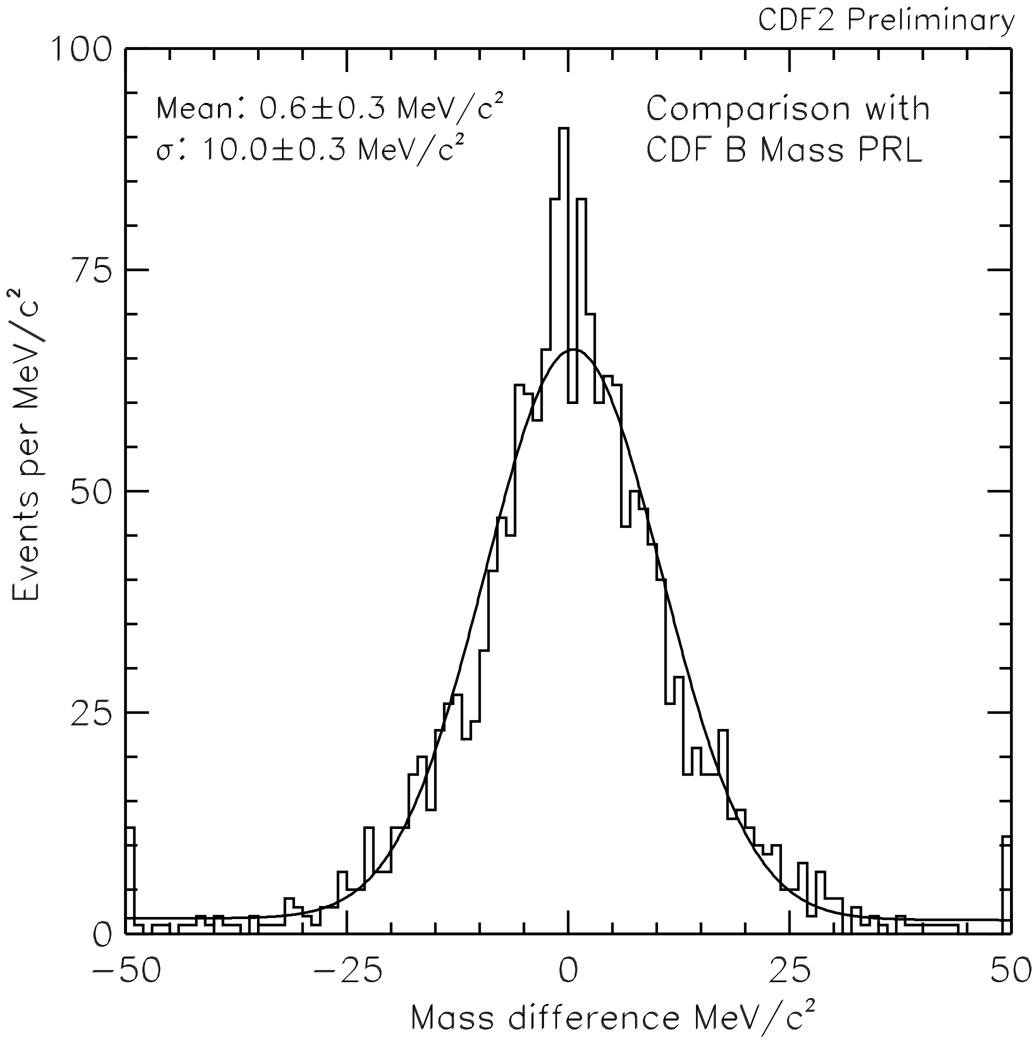


FIG. 7: The event-by-event mass difference of $B^- \rightarrow J/\psi\ K^-$ candidates as determined by a prior CDF publication and this analysis.

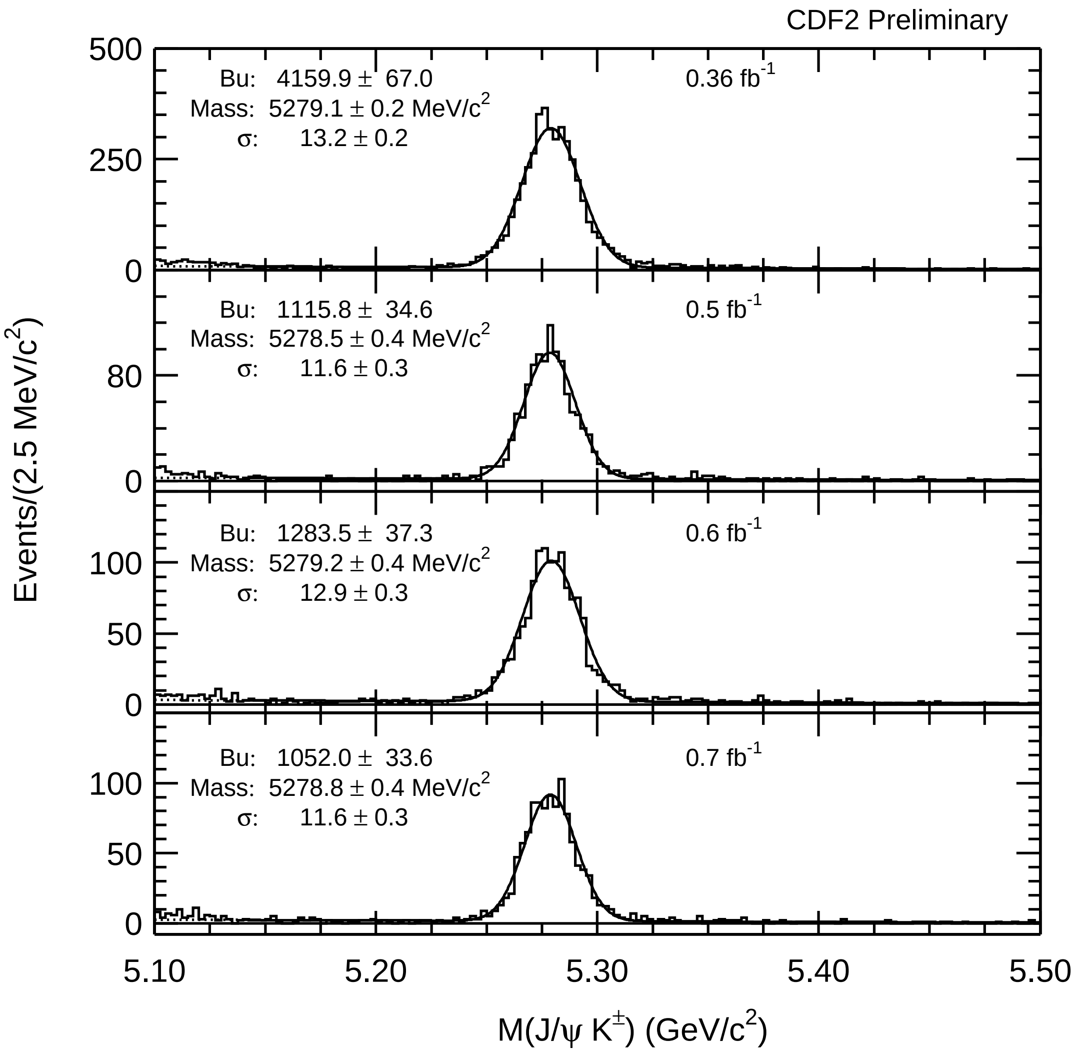


FIG. 8: The fitted mass distribution of $J/\psi\ K^-$ candidates for different run ranges collected Run II.Shown are the incremental events collected in each data period.

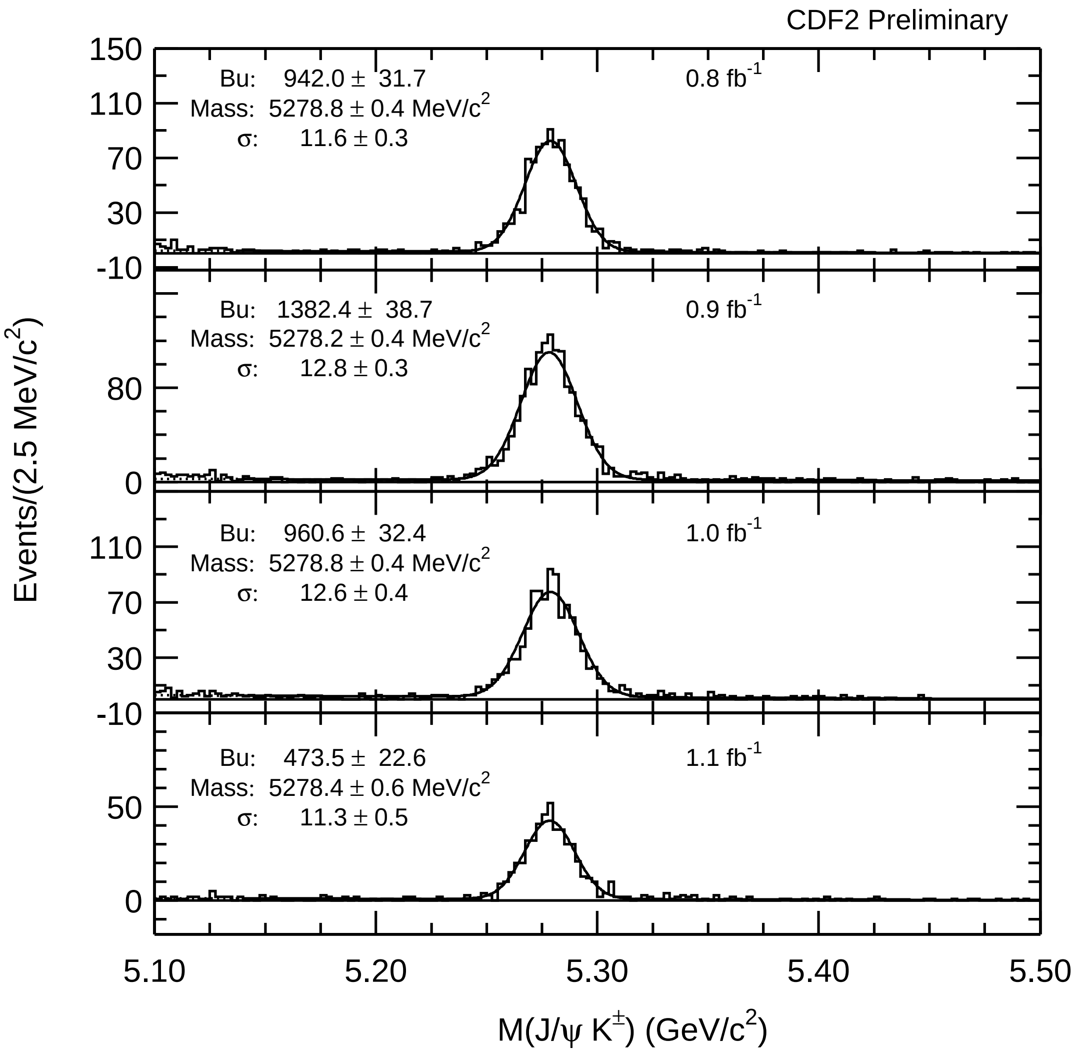


FIG. 9: The fitted mass distribution of $J/\psi\ K^-$ candidates for different run ranges collected Run II. Shown are the incremental events collected in each data period.

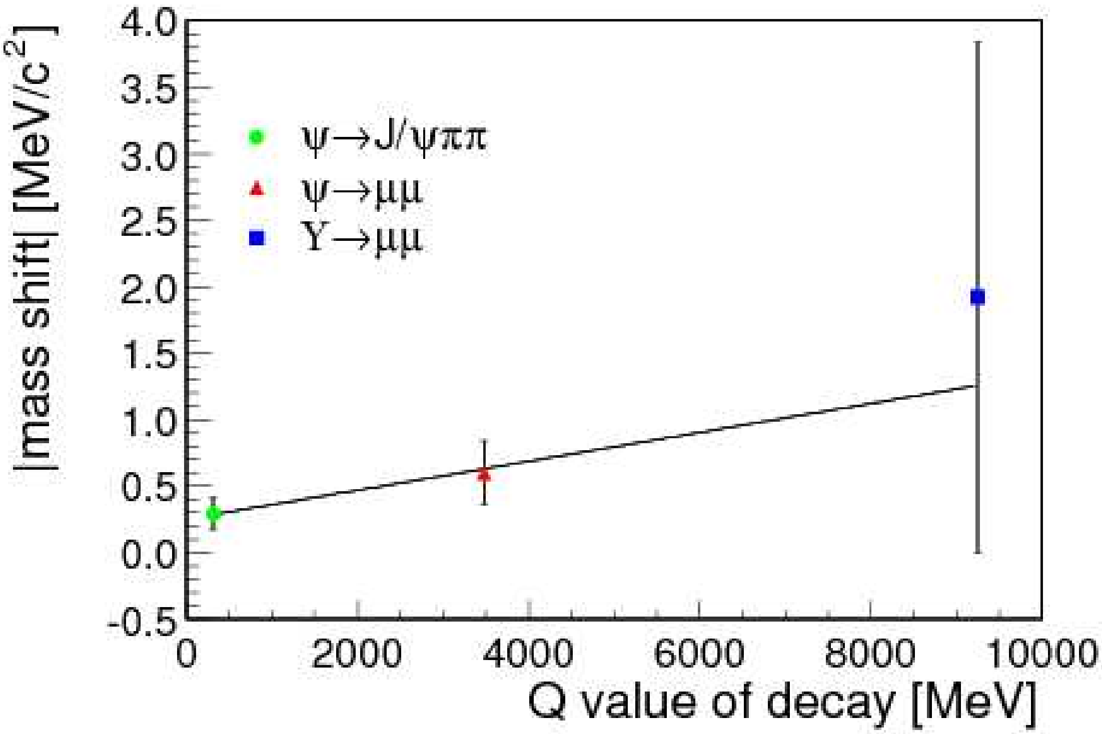


FIG. 10: The uncertainty in mass determinate due to momentum scale uncertainties as a function of the Q-value of the decay.

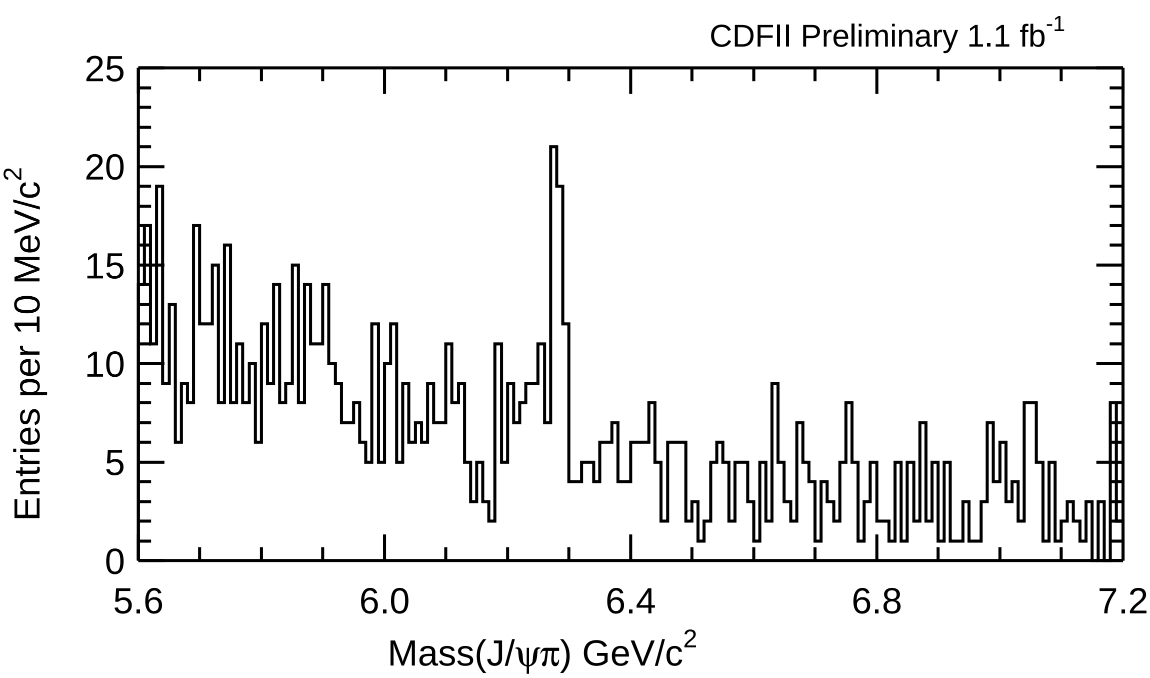


FIG. 11: The invariant mass distribution of $B_c^- \to J/\psi\ \pi^-$ candidates.